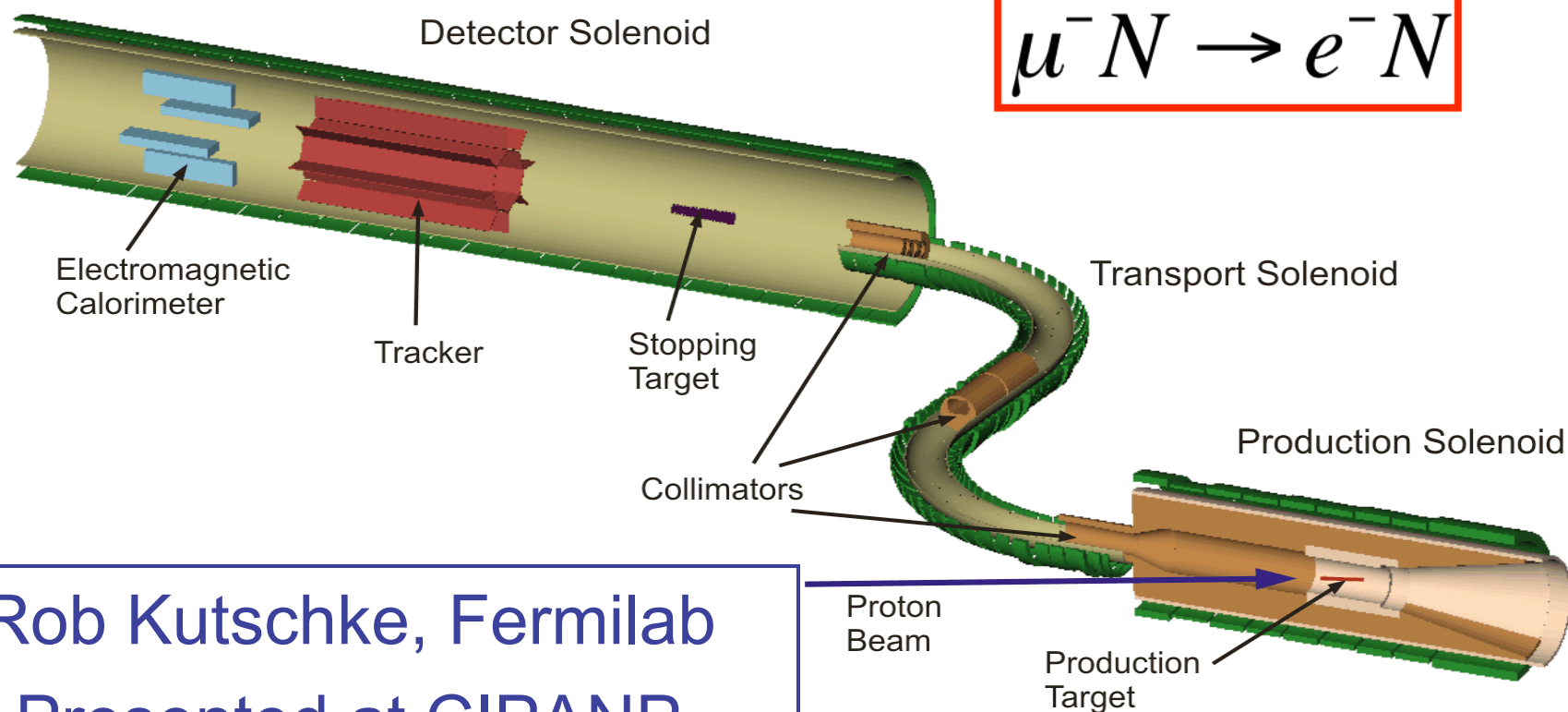


Mu2e-doc-546-v6



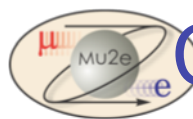
The Mu2e Experiment at Fermilab

$$\mu^- N \rightarrow e^- N$$



Rob Kutschke, Fermilab
Presented at CIPANP
May 30, 2009

<http://mu2e.fnal.gov>

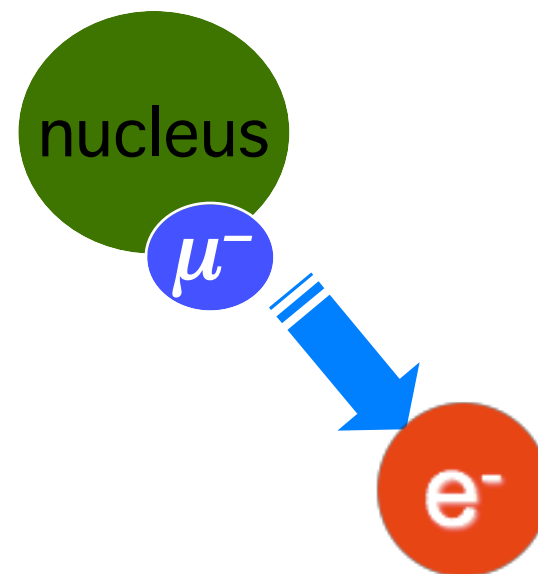


Coherent Neutrino-less μ to e Conversion

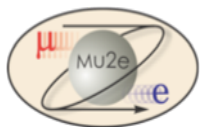


$$\mu^- N \rightarrow e^- N$$

- Initial state: muonic atom
- Final state:
 - Single mono-energetic electron.
 - Energy depends on Z of target.
 - Recoiling nucleus (not observed).
 - Coherent: nucleus stays intact.
- Negligible rate in Standard Model.
- Observable in many New Physics scenarios.
- Related decays: Charged Lepton Flavor Violation (CLFV):



$$\begin{aligned} \mu &\rightarrow e\gamma & \mu &\rightarrow e^+e^-e^+ & K_L^0 &\rightarrow \mu e & B^0 &\rightarrow \mu e \\ \tau &\rightarrow \mu\gamma & \tau &\rightarrow \mu^+\mu^-\mu^+ & D^+ &\rightarrow \mu^+\mu^+\mu^- \end{aligned}$$

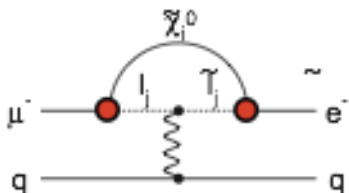


Sensitivity to New Physics



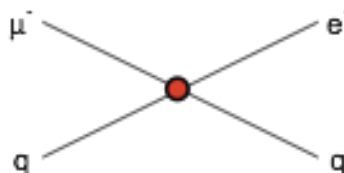
Supersymmetry

rate $\sim 10^{-15}$



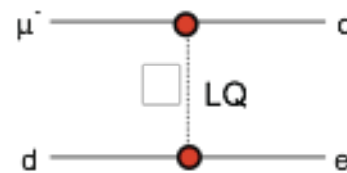
Compositeness

$\Lambda_c \sim 3000 \text{ TeV}$



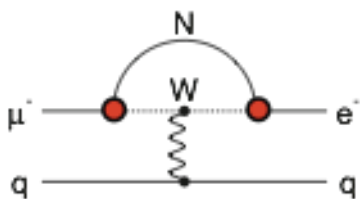
Leptoquark

$M_{LQ} = 3000 (\lambda_{\mu d} \lambda_{e d})^{1/2} \text{ TeV}/c^2$



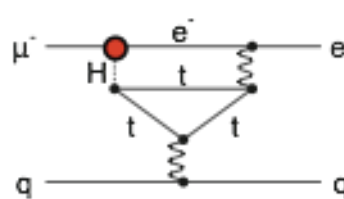
Heavy Neutrinos

$|U_{\mu N} U_{e N}|^2 \sim 8 \times 10^{-13}$



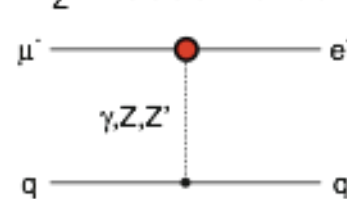
Second Higgs Doublet

$g(H_{\mu e}) \sim 10^{-4} g(H_{\mu \mu})$



Heavy Z' Anomal. Z Coupling

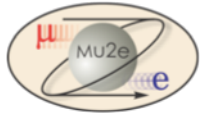
$M_{Z'} = 3000 \text{ TeV}/c^2$



Sensitive to mass scales up to $O(10,000 \text{ TeV})!$

Do not contribute to $\mu \rightarrow e \gamma$

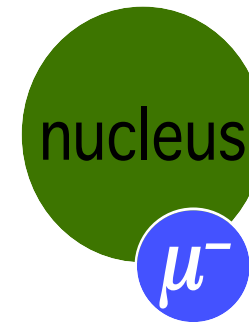
See Flavour physics of leptons and dipole moments, [arXiv:0801.1826](https://arxiv.org/abs/0801.1826)



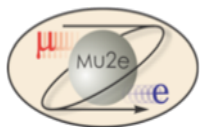
Mu2e in One Page



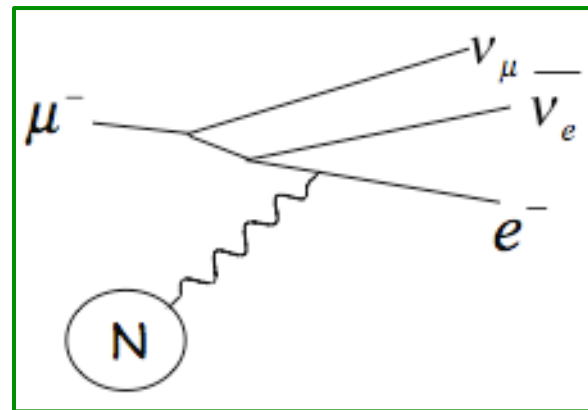
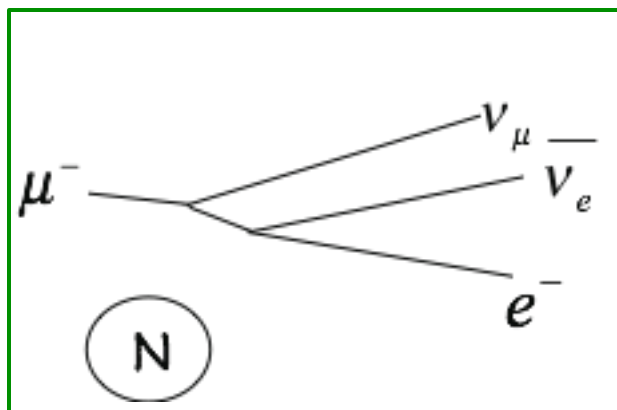
- Make muonic Al.
- Watch it decay:
 - Decay-in-orbit (DIO): 40%
 - Continuous E_e spectrum.
 - Muon capture on nucleus: 60%
 - Nuclear breakup: p, n, γ
 - **Neutrino-less μ to e conversion**
 - Mono-energetic $E_e \approx 105$ MeV
 - At endpoint of continuous spectrum.
- Measure E_e spectrum.
- Design of muon beamline and detector motivated by MECO, which was motivated by MELC.



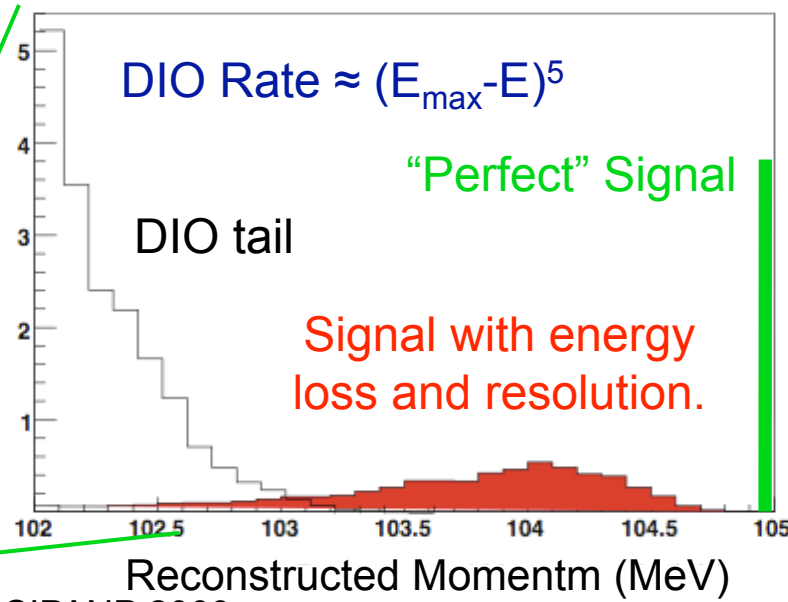
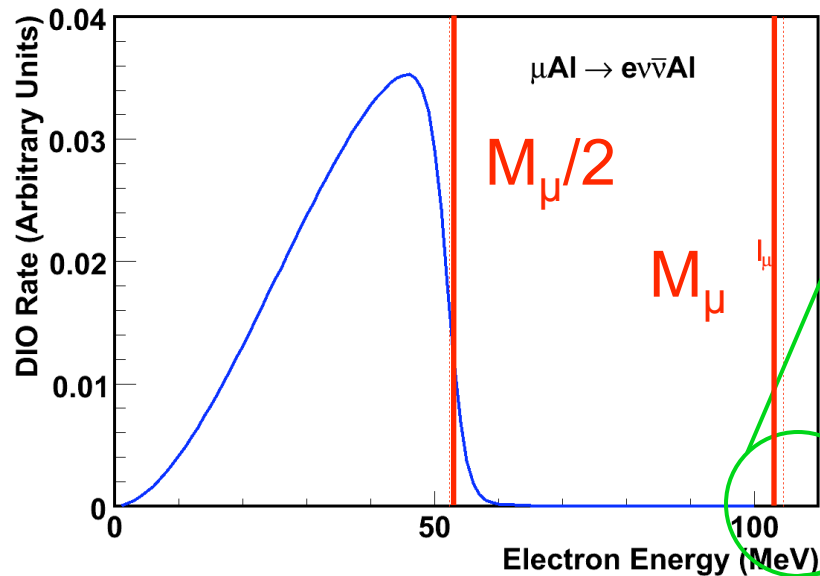
Bohr radius ≈ 20 fm
Al nuclear radius ≈ 4 fm
Lifetime: 864 ns

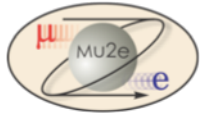


Decay-in-Orbit: Dominant Background



1.5×10^{-15} DIO e^- are with 2 MeV of endpoint.



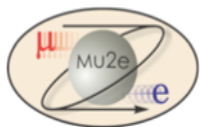


What do We Measure?

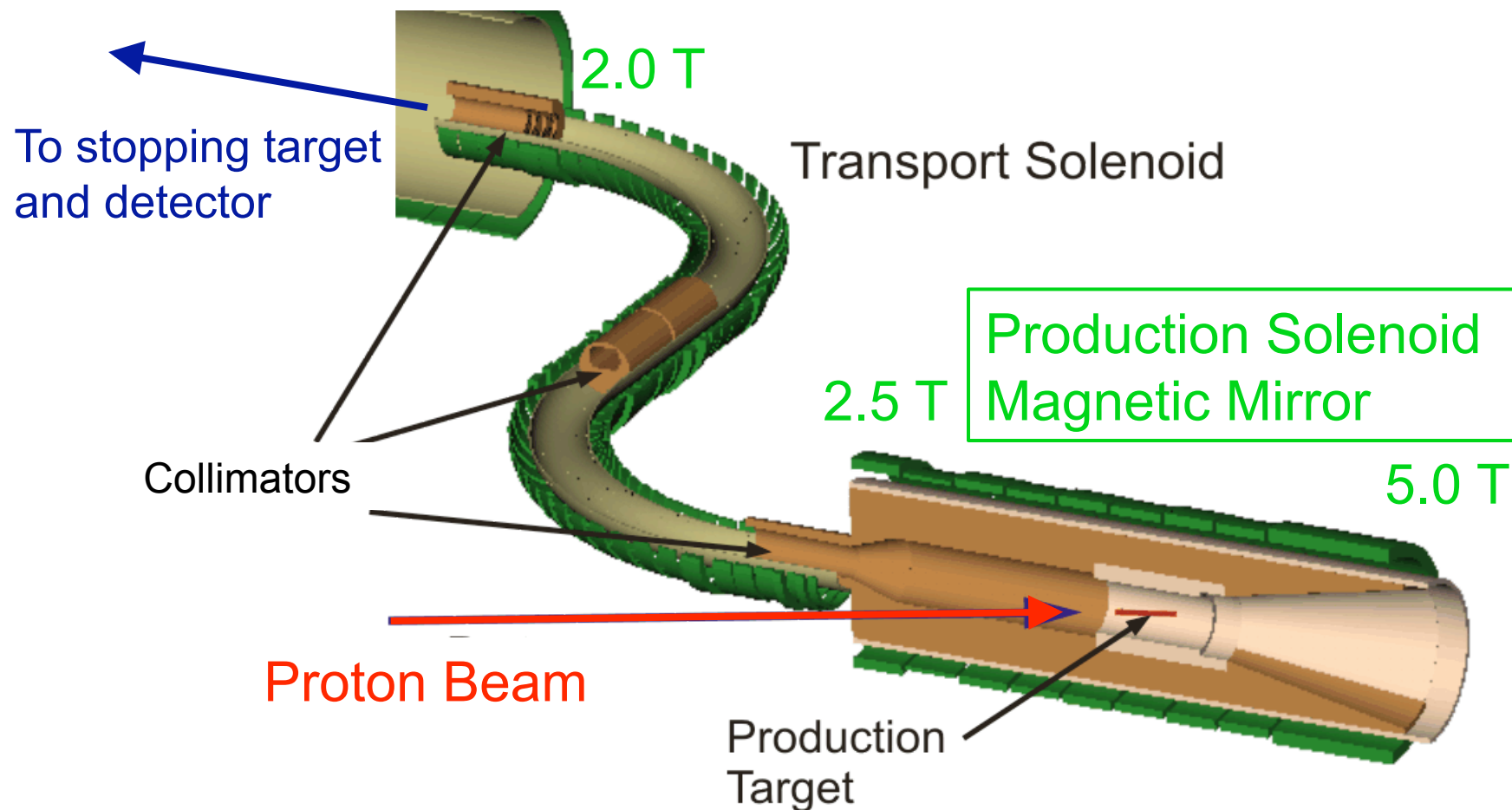


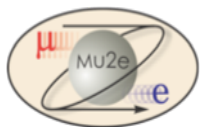
$$R_{\mu e} = \frac{\Gamma(\mu^- + (A, Z) \rightarrow e^- + (A, Z))}{\Gamma(\mu^- + (A, Z) \rightarrow \nu_\mu + (A, Z - 1))}$$

- Numerator:
 - Do we see an excess at the E_e end point?
- Denominator:
 - Normal muon capture on Al.
- Sensitivity for a 2 year run (2×10^7 seconds).
 - $\approx 2.3 \times 10^{-17}$ single event sensitivity.
 - $< 6 \times 10^{-17}$ limit at 90% C.L.
- 10,000 \times better than previous limit (SINDRUM II).

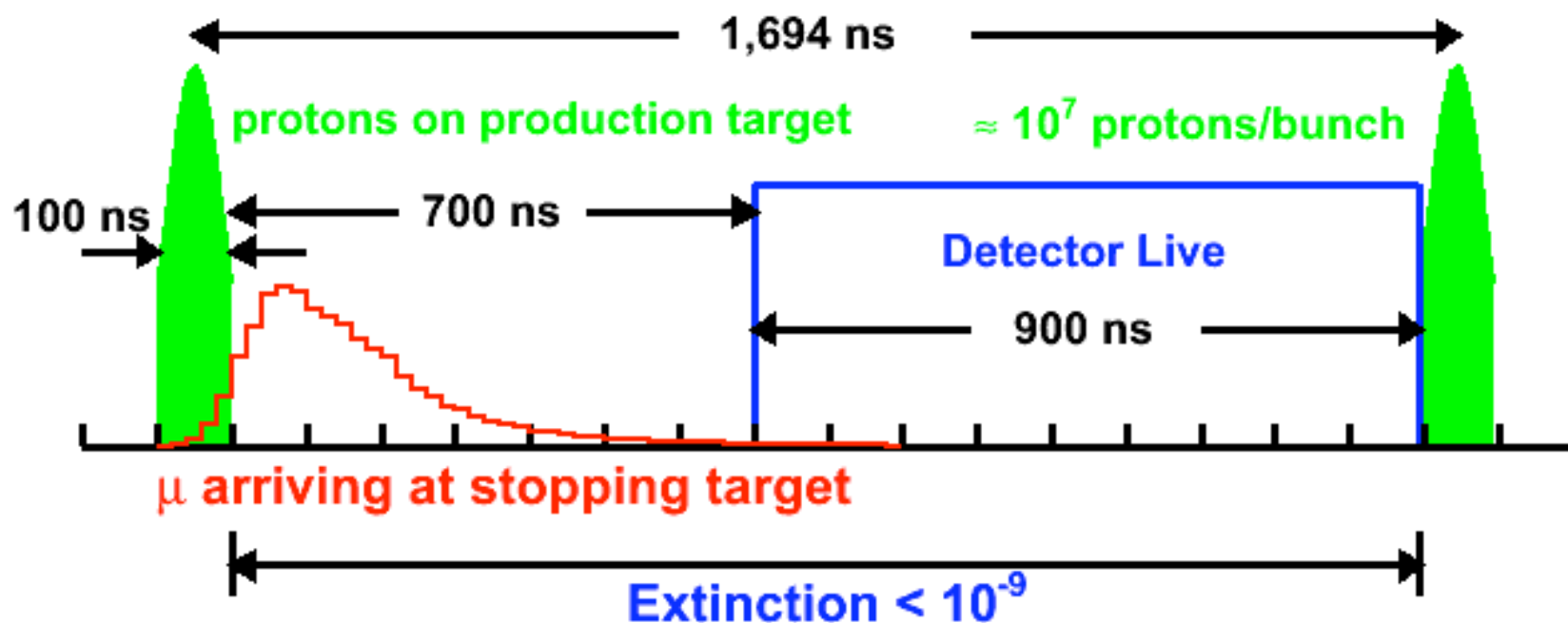


Back Scattered Muon Beam

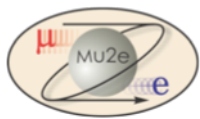




One Cycle of the Muon Beamline

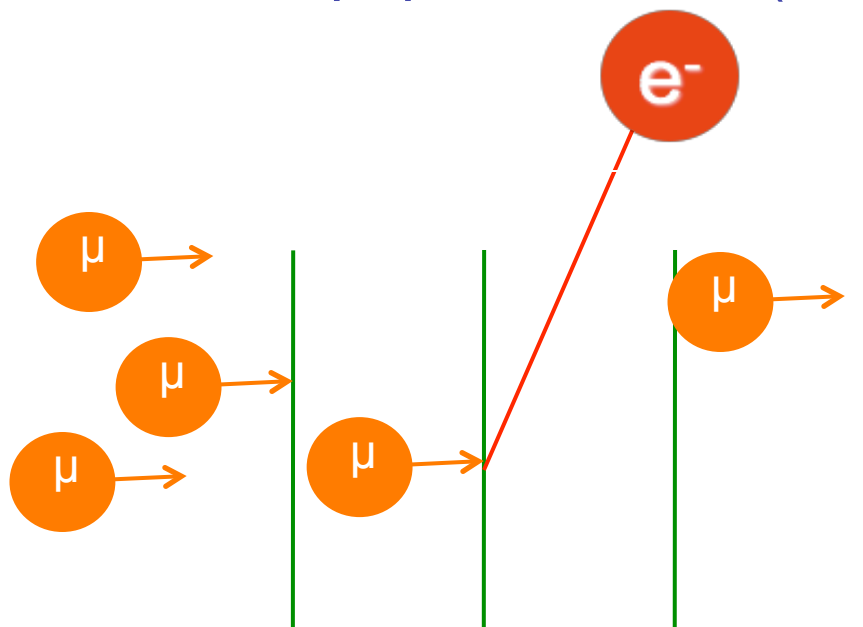


- μ^- are accompanied by e^- , π^- , ...
- Extinction required to reduce backgrounds.
 - 1 out of time proton per 10^9 in time protons.
- Lifetime of muonic Al: 864 ns.

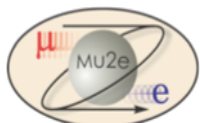


Stopping Target

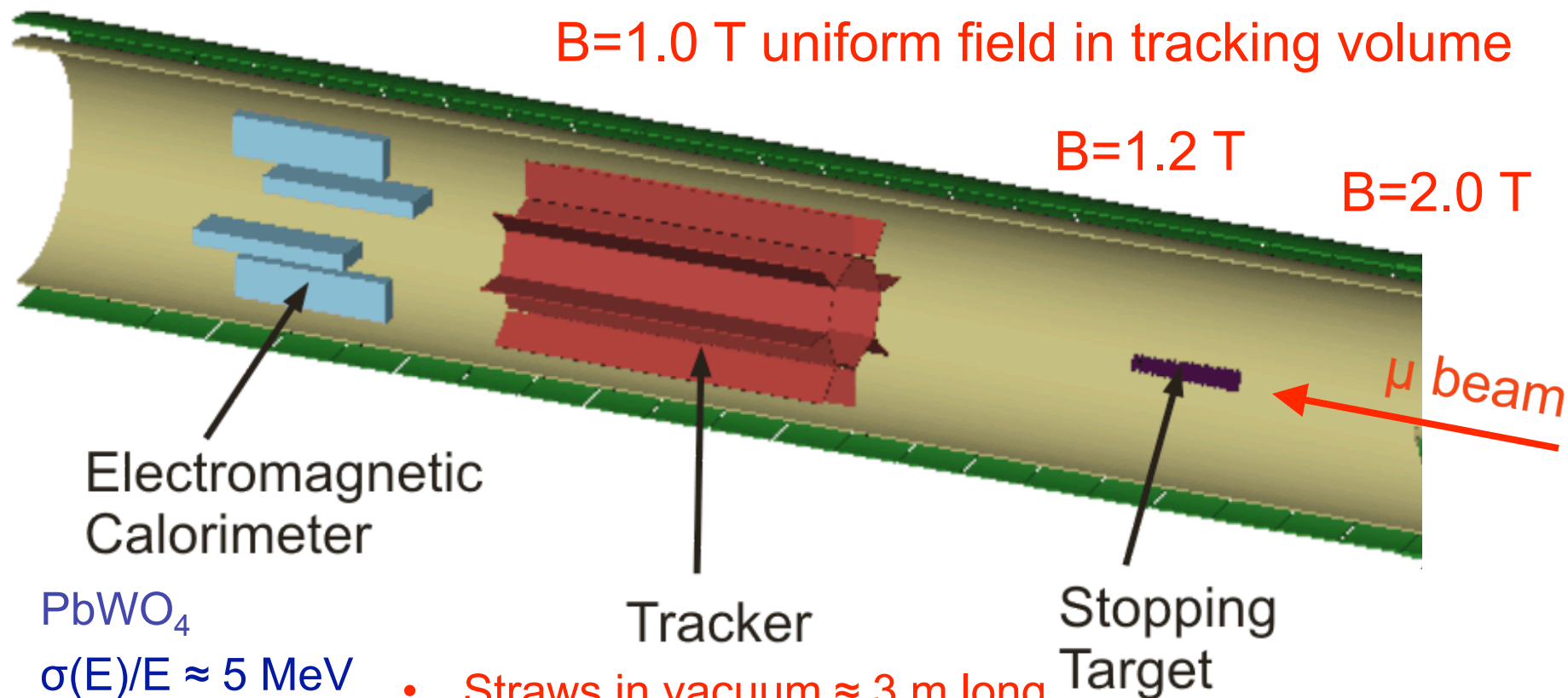
- Pulse of low energy μ^- on thin Al foils; $\approx 60\%$ capture.
- 1 stopped μ^- per 400 protons on production target.
- Wait for prompt backgrounds to go away.
- Electrons pop out of foils (lifetime of 864 ns)



- 17 target foils
- 200 microns thick
- 5 cm spacing
- Radius:
 - ≈ 10 . cm at upstream
 - ≈ 6.5 cm at downstream

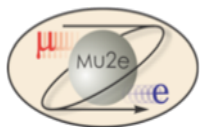


Detector Solenoid and Detector



- PbWO_4
- $\sigma(E)/E \approx 5 \text{ MeV}$
- Trigger + confirmation of track.

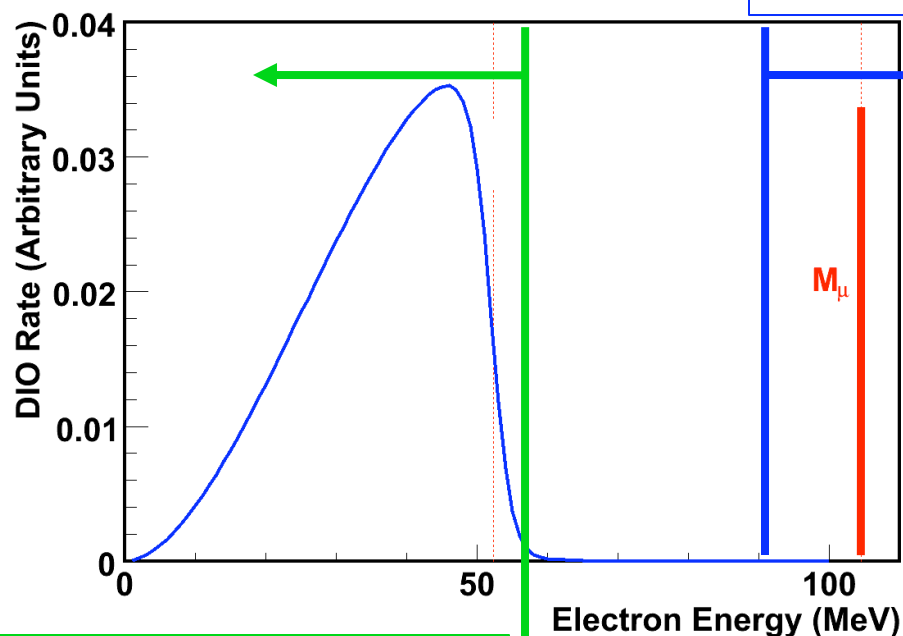
- Straws in vacuum $\approx 3 \text{ m}$ long
- Cathode pads for z position
- Geom + reco efficiency: $\approx 20\%$
- $\sigma(p) \approx 150 \text{ keV}$ at $p=105 \text{ MeV}$



How do you measure 2×10^{-17} ?

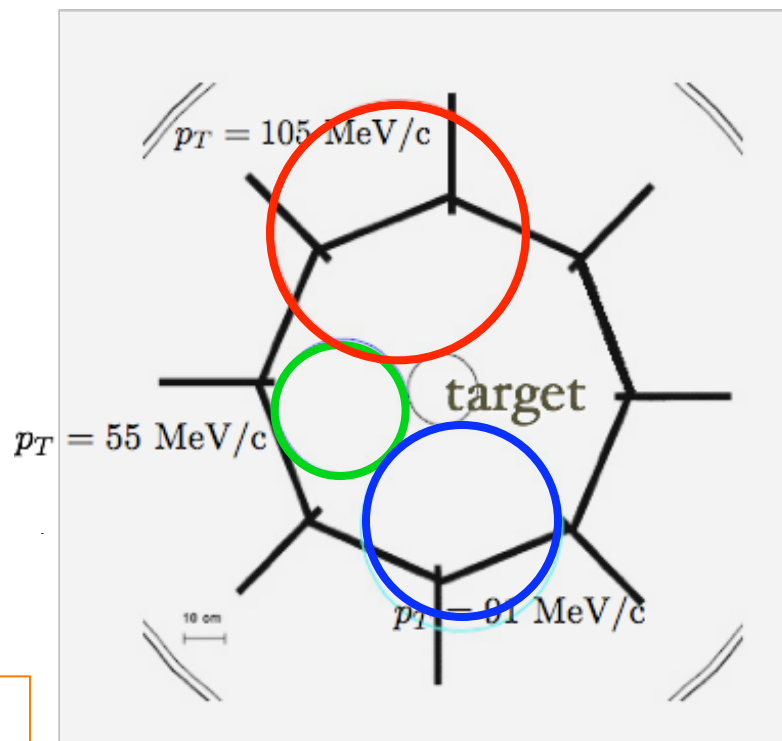


Reconstructable tracks

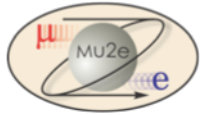


No hits in detector

Some hits in detector.
Tracks not reconstructable.



Beam's-eye view of Tracker



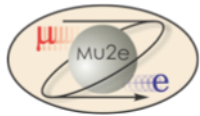
Backgrounds for 2×10^7 s Running



Source	Events	Comment
μ decay in orbit	0.225	
Radiative π^- capture*	0.063	From protons during detection time
Beam electrons*	0.036	
μ decay in flight*	0.036	With scatter in target
Cosmic ray induced	0.016	Assumes 10^{-4} veto inefficiency
Other	0.039	6 other processes
Total	0.42	

*: scales with extinction; values in table assume extinction of 10^{-9} .

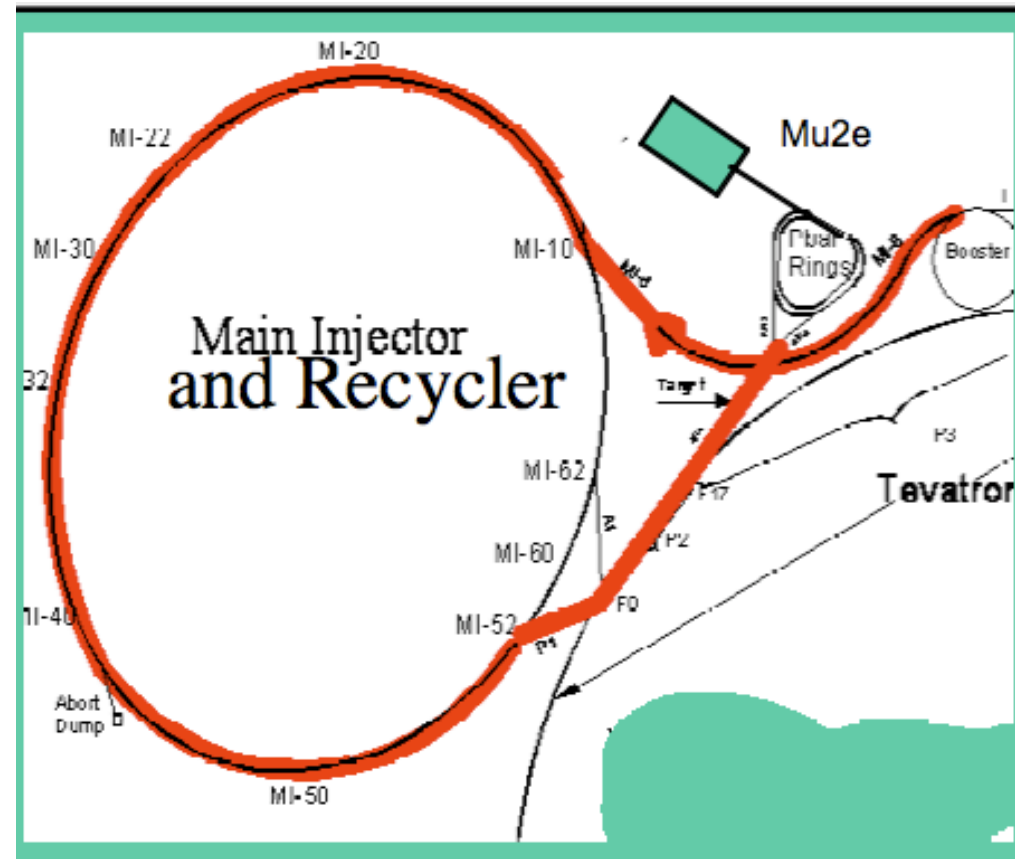
- Reduce DIO BG with excellent energy resolution, obtained by careful design of the tracker.
- Reduce next tier BGs with extinction.
- Reduce cosmic ray BG with shielding and veto.



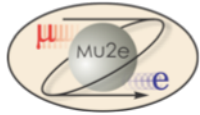
Proton Delivery and Economics



- Reuse existing Fermilab facilities with modest modifications.
- p-bar complex: 2 rings.
 - Use one ring as a “stash”.
 - Slow spill from the other.
 - 90% duty cycle slow spill.
 - Other schemes under study.
- Sharing p's with NOVA:
 - NOVA 12/20 booster cycles.
 - Mu2e will use 6/20 cycles.



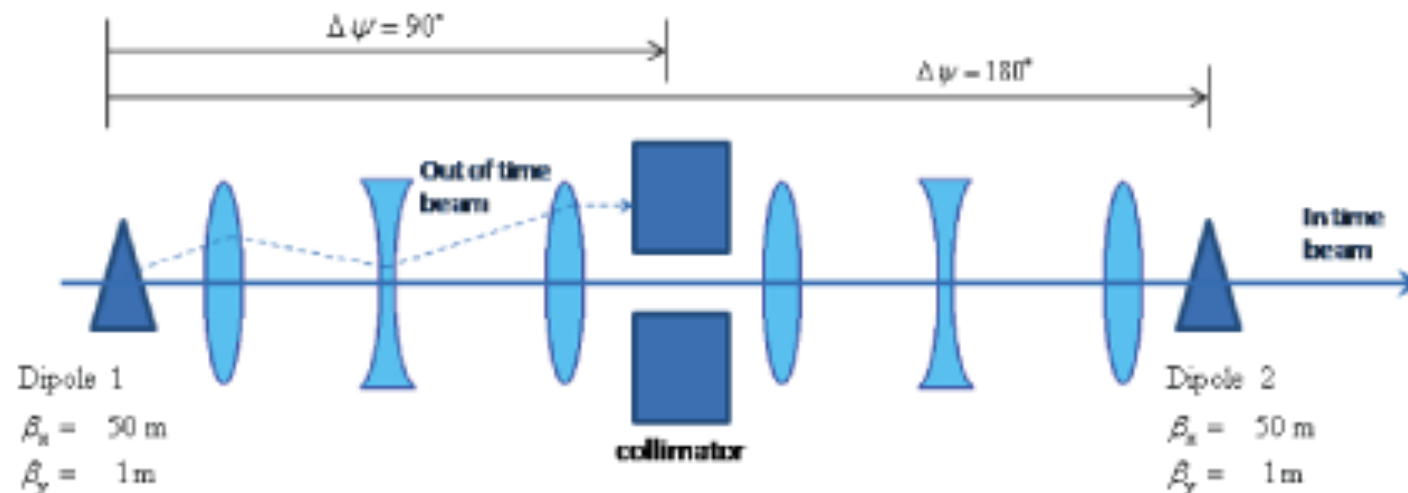
Making a stable, slow spill with a very intense proton beam is a big challenge.

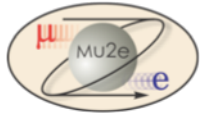


Required Extinction 10^{-9}



- Internal: 10^{-7} already demonstrated at AGS.
 - Without using all of the tricks.
 - Normal FNAL: 10^{-2} to 10^{-3} ; but better has not yet been needed.
- External: in transfer-line between ring and production target.
 - Fast cycling dipole kickers and collimators.
- Monitoring techniques under study.





Estimated Cost and Schedule



- Estimated Total Project Cost O(M\$200.).
 - Fully loaded, escalated. Overall contingency $\approx 50\%$.
- Critical path: solenoids.
 - Technically limited schedule:

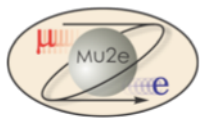
Solenoids	2009	2010	2011	2012	2013	2014	2015	2016
Conceptual Design								
Final Design/Place orders								
Construction/Installation/ Commissioning								

- R&D going on now or soon.
 - PSI: products of μ capture on Al.
 - FNAL: Extinction tests; straw tests.



Now

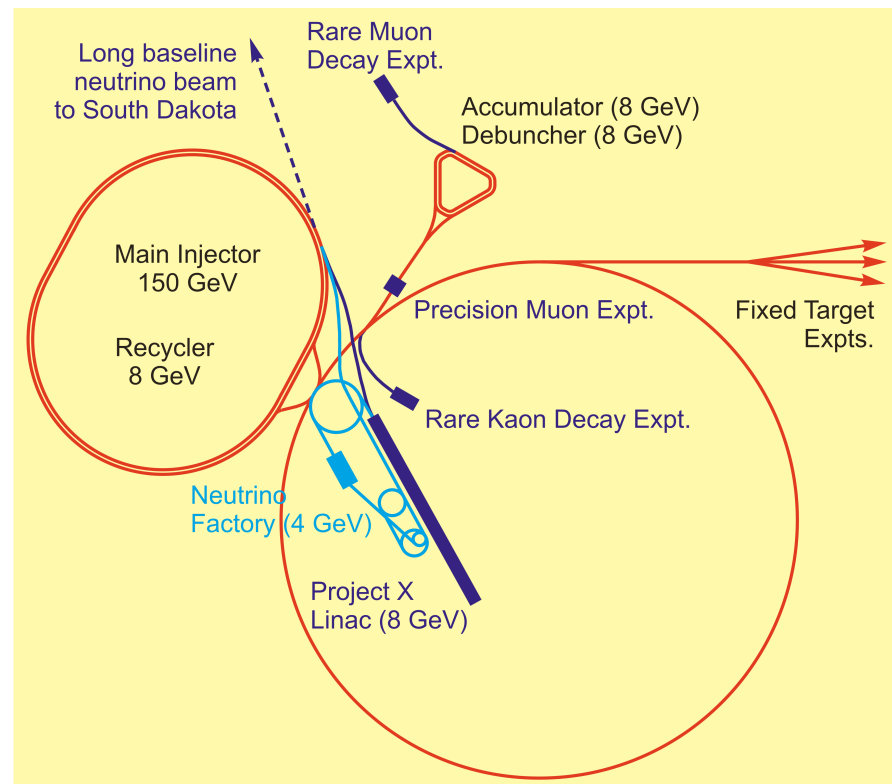
Opportunities for
university groups.

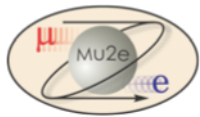


Mu2e In the Project X Era



- Project X: high intensity proton source to replace existing Booster.
 - Booster: 20 kW beam power at 8 GeV.
 - Project X: 200 kW at 8 GeV (with upgrade path to 2000 kW).
 - With corresponding upgrades at 120 GeV.
- If we have a signal:
 - Study Z dependence by changing stopping target.
 - Helps disentangle the underlying physics.
- If we have no signal:
 - Up to to 100 × Mu2e physics reach, $R_{\mu e} < 10^{-18}$.
 - First factor of ≈ 10 can use the same detector.

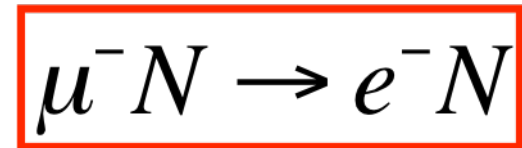


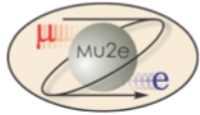


Summary and Conclusions



- Sensitivity for 2 years of running:
 - $R_{\mu e} < 6 \approx 10^{-17}$ @ 90% CL.
 - 10,000 \times better than previous best limit.
 - Mass scales to O(10,000 TeV) are within reach.
- Many SUSY@LHC scenarios predict $R_{\mu e} \approx 10^{-15}$,
 - Expect 40 events with < 0.5 events BG.
- Strongly endorsed by P5. Stage I approval from Fermilab.
- Critical path is the solenoid system:
 - Technically limited schedule: startup possible in 2016.
- Project X era:
 - If a signal, we can study N(A,Z) dependence.
 - If no signal, improve sensitivity up to 100 \times , $R_{\mu e} < O(10^{-18})$.

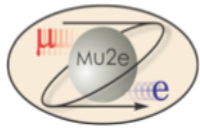




For Further Information

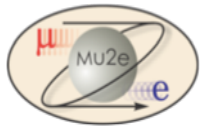


- Mu2e home page: <http://mu2e.fnal.gov>
- Mu2e Document Database:
 - <http://mu2e-docdb.fnal.gov/cgi-bin/DocumentDatabase>
 - Mu2e Proposal: [Mu2e-doc-388](#)
 - Mu2e [Conference presentations](#)



Backup Slides



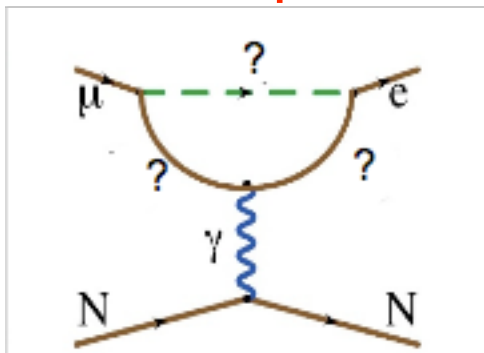


Model Independent Parameterization



$$\mathcal{L}_{\text{CLFV}} = \frac{m_\mu}{(\kappa + 1)\Lambda^2} \bar{\mu}_R \sigma_{\mu\nu} e_L F^{\mu\nu} + \frac{\kappa}{(1 + \kappa)\Lambda^2} \bar{\mu}_L \gamma_\mu e_L (\bar{u}_L \gamma^\mu u_L + \bar{d}_L \gamma^\mu d_L)$$

Loops

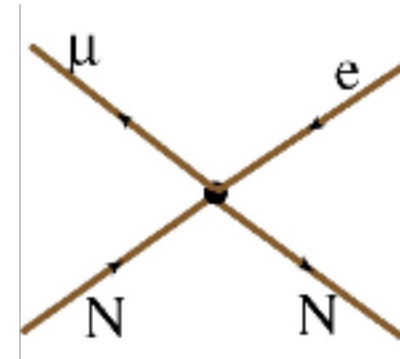


Contributes to $\mu \rightarrow e\gamma$

SUSY and massive neutrinos

Dominates if $\kappa \ll 1$

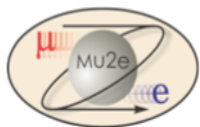
Contact terms



Does not produce $\mu \rightarrow e\gamma$

Exchange of a heavy particle

Dominates if $\kappa \gg 1$

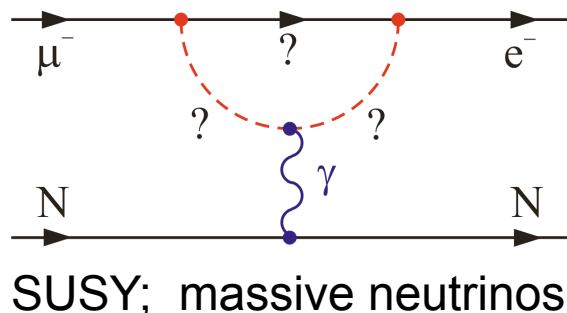


Sensitivity to High Mass Scales



$$\mathcal{L}_{\text{CLFV}} = \frac{m_\mu}{(\kappa + 1)\Lambda^2} \bar{\mu}_R \sigma_{\mu\nu} e_L F^{\mu\nu} + \frac{\kappa}{(1 + \kappa)\Lambda^2} \bar{\mu}_L \gamma_\mu e_L (\bar{u}_L \gamma^\mu u_L + \bar{d}_L \gamma^\mu d_L)$$

Loops

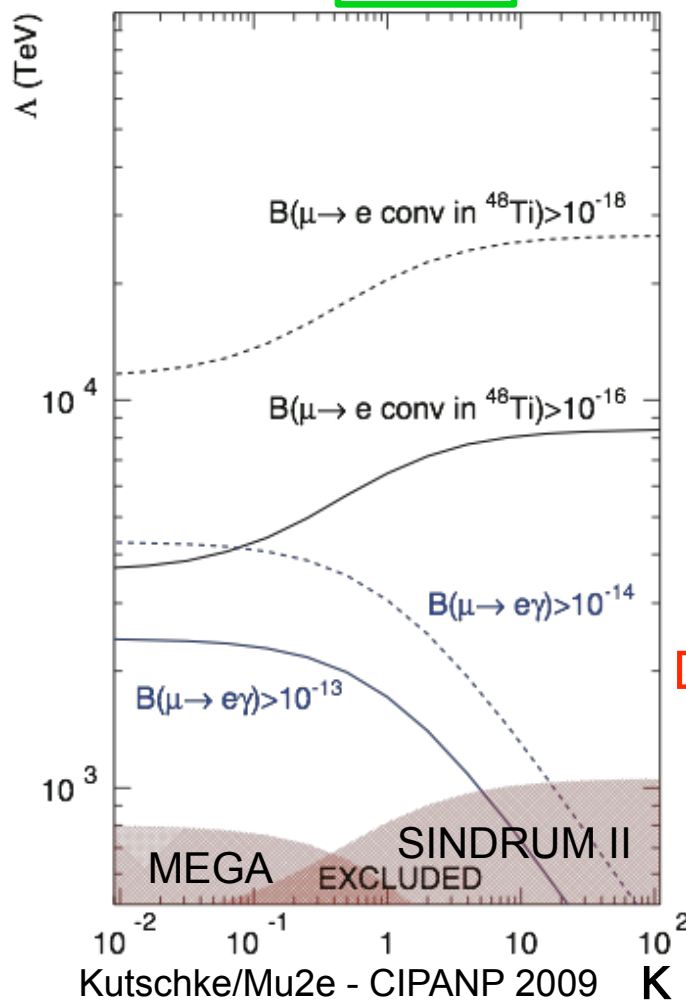


Dominates if $\kappa \ll 1$

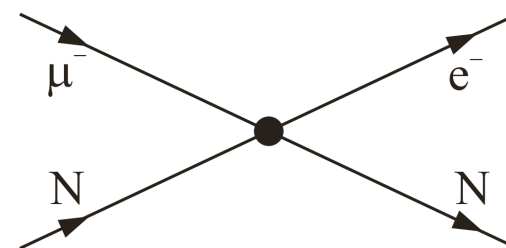
Contributes to $\mu \rightarrow e\gamma$

$$\Gamma(\mu \rightarrow e\gamma) \approx 300 \Gamma(\mu N \rightarrow eN)$$

5/30/09



Contact terms



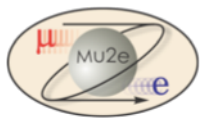
Exchange of a new massive particle

Dominates if $\kappa \gg 1$

Does not produce $\mu \rightarrow e\gamma$

$$\Gamma(\mu N \rightarrow eN) \gg \Gamma(\mu \rightarrow e\gamma)$$

21



Previous Best Experiment



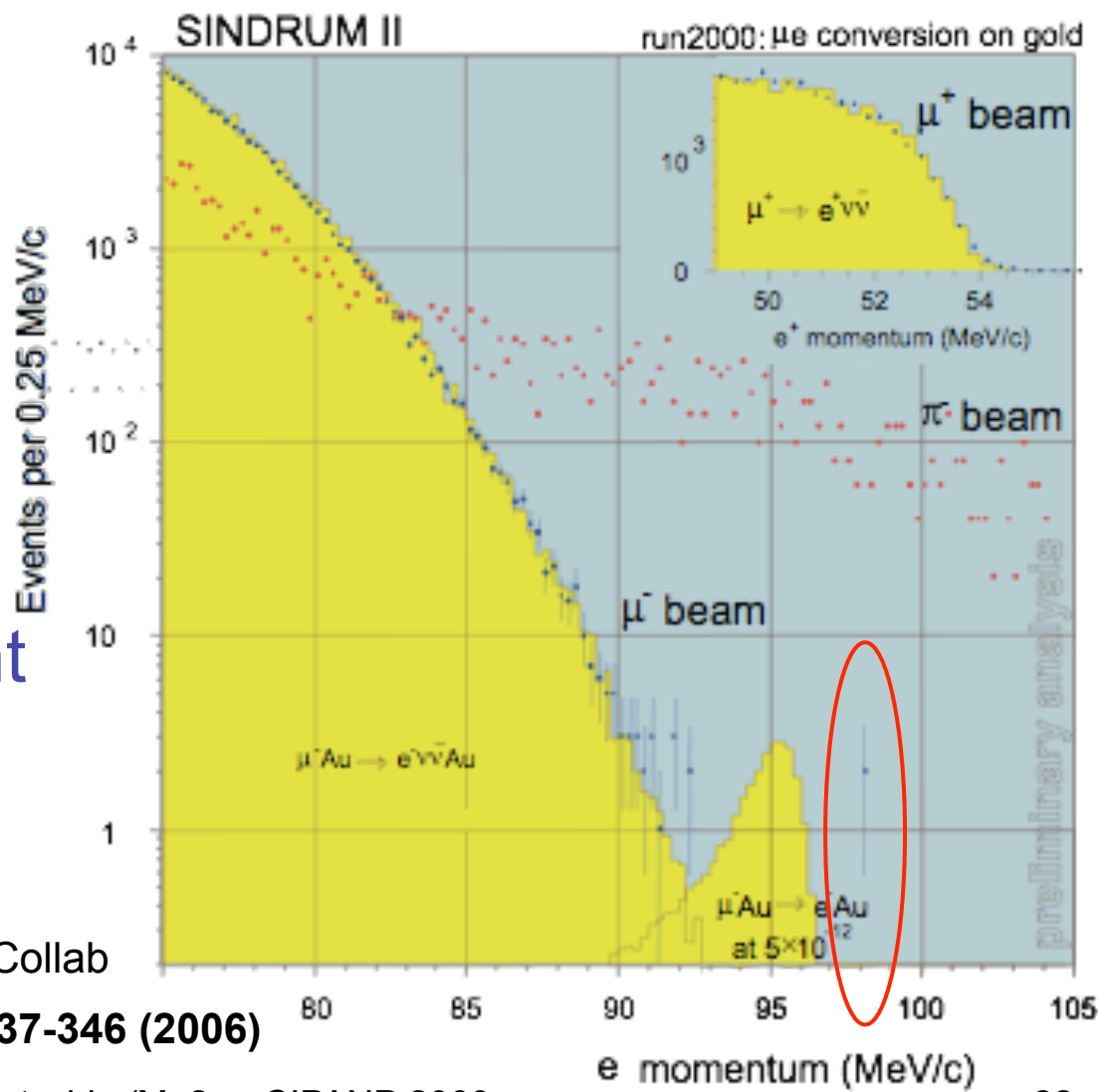
- SINDRUM II
- $R_{\mu e} < 6.1 \times 10^{-13}$
@90% CL
- 2 events in signal region
- Au target: different E_e endpoint than Al.

HEP 2001 W. Bertl – SINDRUM II Collab

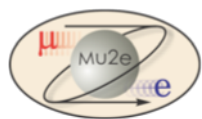
W. Bertl et al, Eur. Phys. J. C **47**, 337-346 (2006)

5/30/09

Kutschke/Mu2e - CIPANP 2009



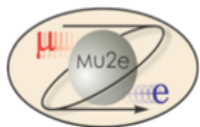
22



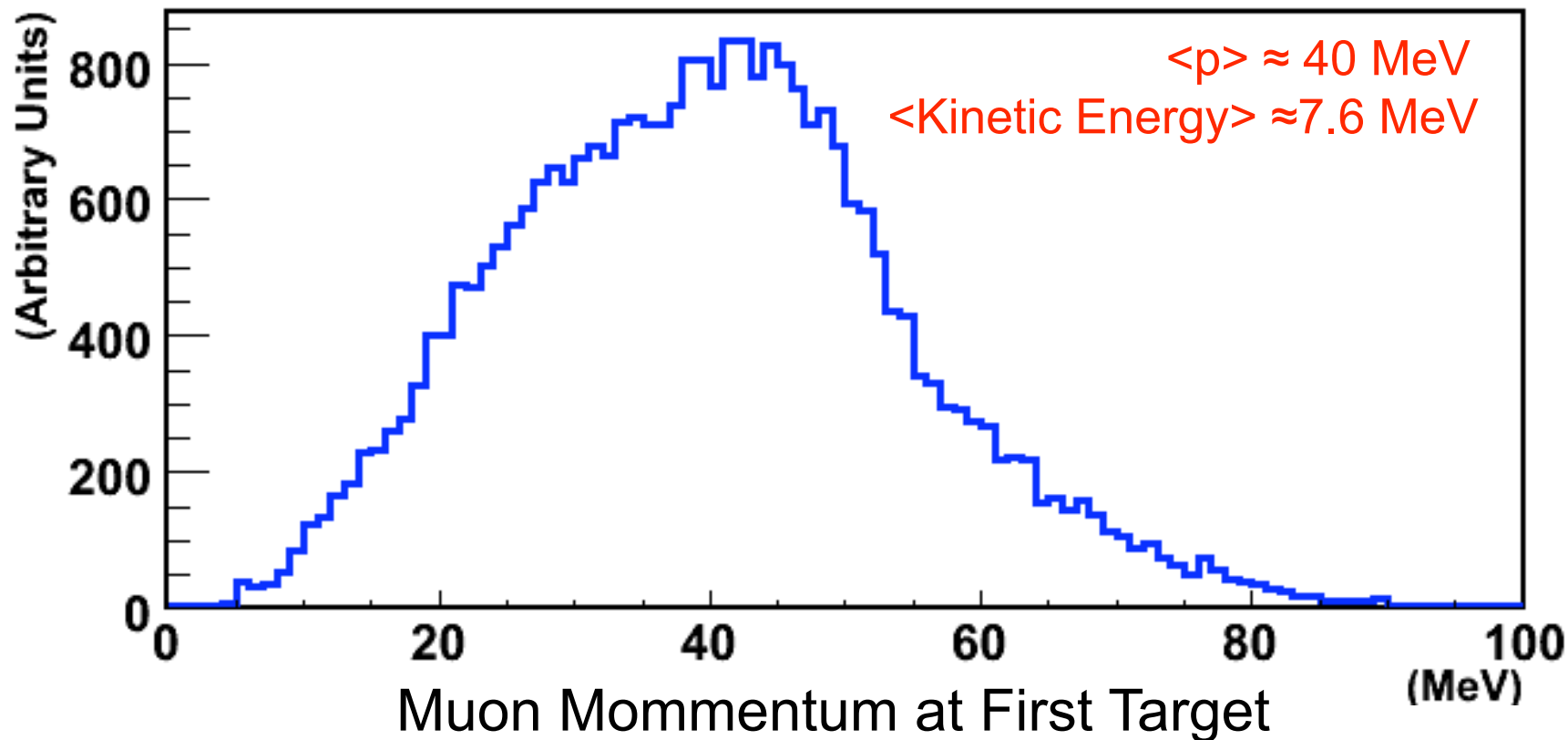
Why Mu2e Better than SINDRUM II?

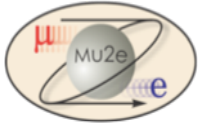


- FNAL can deliver $\approx 1000 \times$ proton intensity.
- Higher μ collection efficiency.
- SINDRUM II was BG limited.
 - Radiative π capture.
 - Bunched beam and excellent extinction reduce this.
- So Mu2e can effectively use the higher proton rate.

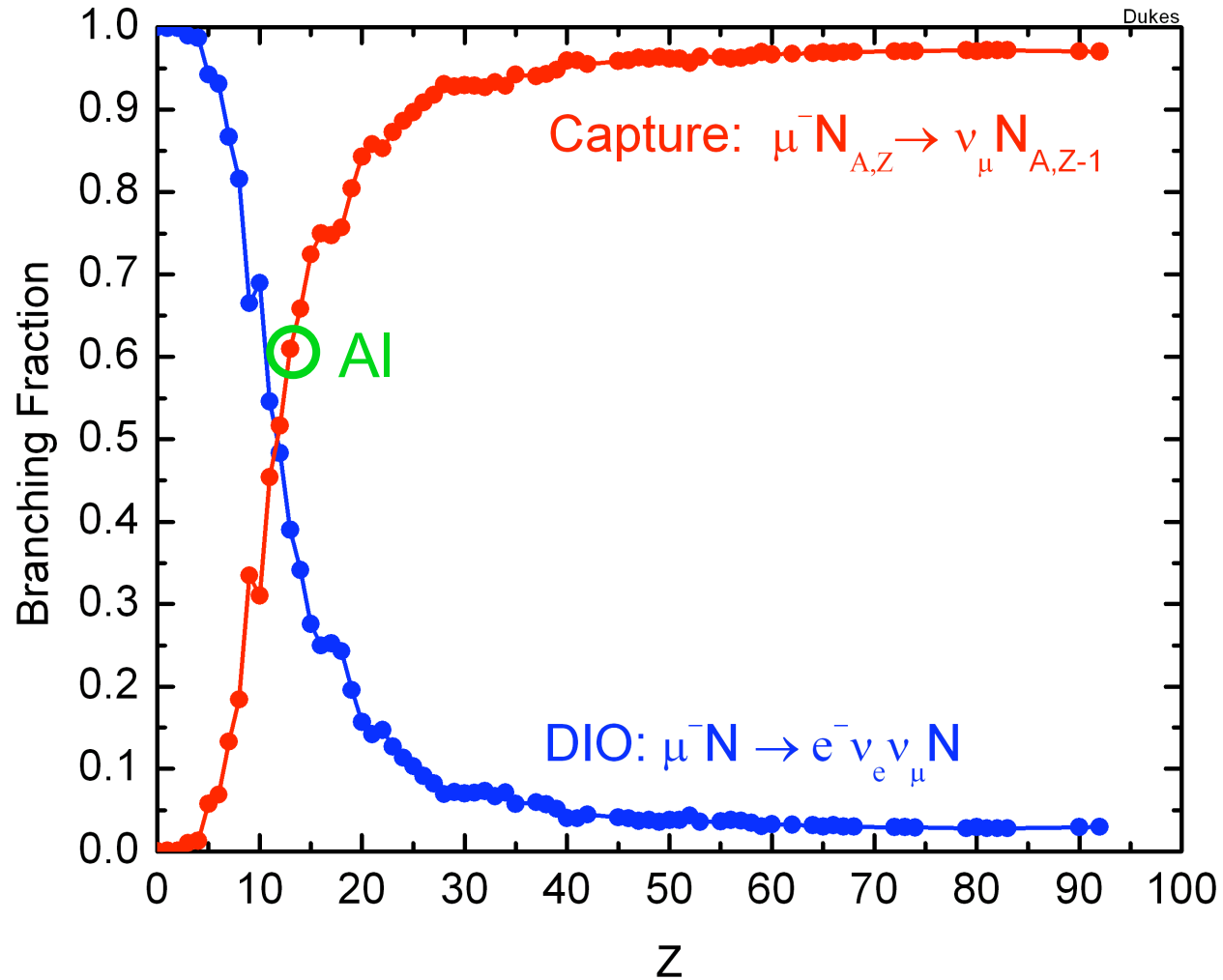


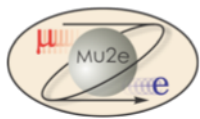
Muon Momentum



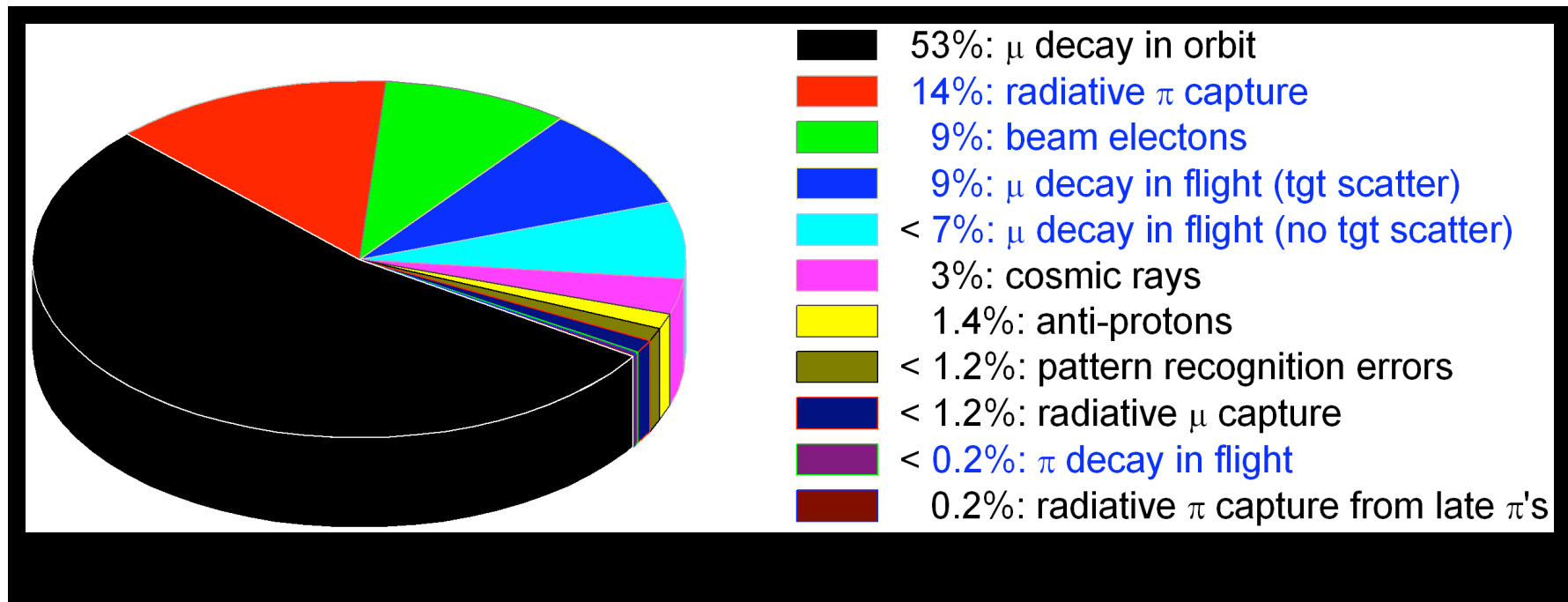


Capture and DIO vs Z

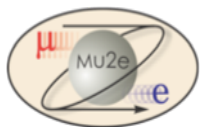




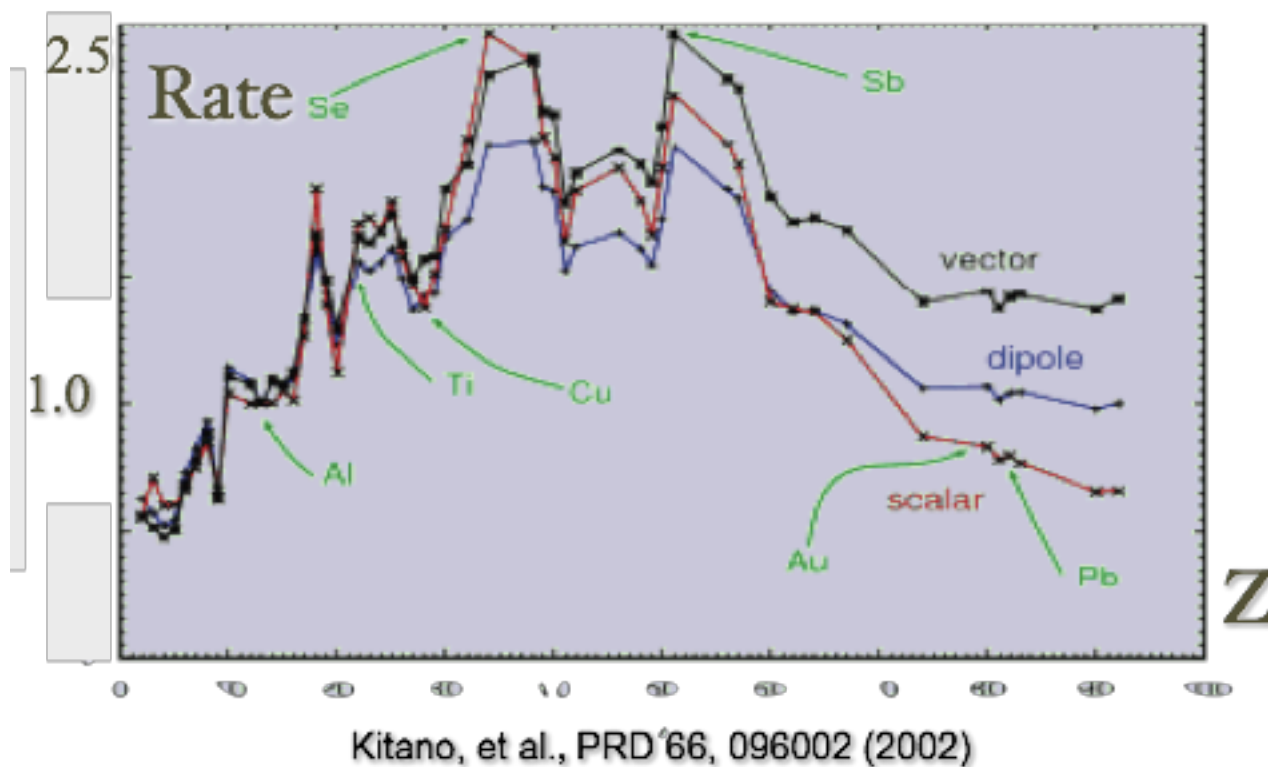
Distribution of Backgrounds

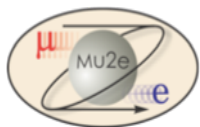


- About 50% of BG comes from protons out of time with bunches.
- In 2×10^7 s of running, estimate:
 - 0.42 background events
 - 40 signal events for $R_{\mu e} = 10^{-15}$.

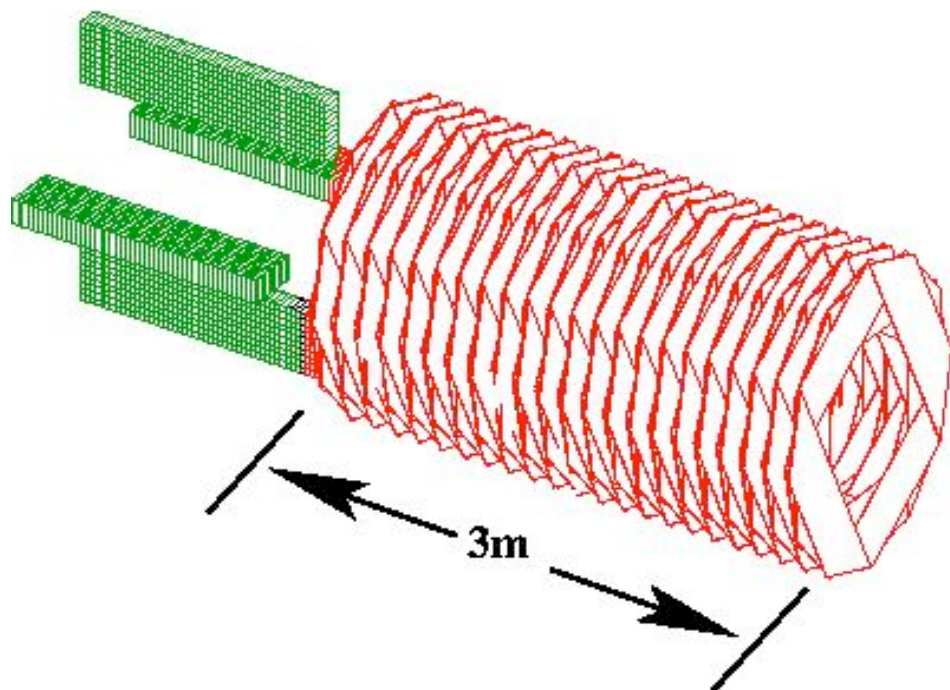


Conversion Rate, Normalized to Al



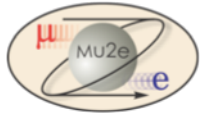


Alternative: T-Tracker



- 260 sub-planes; 60 straws per.
- No cathode pads.
- 5 mm diameter conducting straws
- Length from 70-130 cm
- Total of 13,000 channels

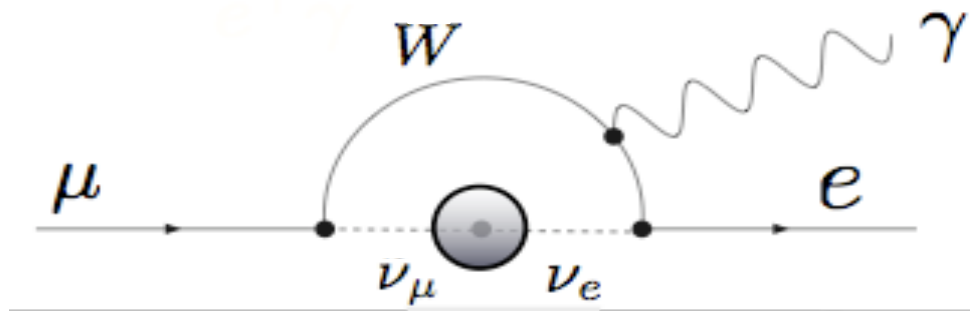
- L-Tracker
 - Not yet sure how to build it?
- T-Tracker
 - Robust pattern recognition may be harder?
- Need a fair head to head comparison.



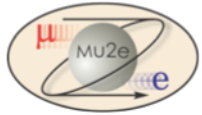
CLFV Rates in the Standard Model



- With massive neutrinos, non-zero rate in SM.
- Too small to observe.



$$\text{BR}(\mu \rightarrow e \gamma) = \frac{3\alpha}{32\pi} \left| \sum_{i=2,3} U_{\mu i}^* U_{ei} \frac{\Delta m_{1i}^2}{M_W^2} \right|^2 < 10^{-54}$$



Backgrounds for 2×10^7 s Running



Source	Events	Comment
μ decay in orbit	0.225	
Pattern Recognition Errors	<0.002	
Radiative μ capture	<0.002	
Beam electrons*	0.036	
μ decay in flight*	<0.027	without scatter in target
μ decay in flight*	0.036	with scatter in target
π^- decay in flight*	<0.001	
Radiative π^- capture*	0.063	from protons during live gate
Radiative π^- capture	0.001	from late arriving π^-
Anti-proton induced	0.006	
Cosmic ray induced	0.016	
Total	0.415	

*: scales with extinction; values in table assume extinction of 10^{-9} .